Hydrogeological investigation in constructed wetlands during pulsing periods

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Introduction

Hydrology and hydrogeology are very important components of wetland research, controlling the ecological functions of wetlands that are often located between terrestrial and aquatic areas. Generally, a direct connection exists between groundwater and surface water. Mitsch and Gosselink (2000), Wurster et al. (2003), and Choi and Harvey (2000) have indicated that "Hydrologic fluxes in lakes and wetlands often include surface inflow and outflow…and exchange between surface water and groundwater". Since direct measurements are usually not applicable, quantification of the interaction between surface and groundwater is difficult, and sometimes surface and groundwater exchange fluxes have been treated as an insignificant component or residual term in the wetland surface-water balance. However, because of large differences between geochemical processes and solutes in surface and groundwater, even a small flux between these compartments might be crucial in altering wetland redox conditions, and thus biochemistry (Howes et al. 1996). Fortunately, hydrological parameters can be quantified in constructed wetlands that are designed and managed artificially, and in which some of the hydrological and ecological conditions can be adjusted on demand.

Studies on regional groundwater flow along the Des Plaines River in northern IL have indicated that groundwater is recharged by wetlands and then discharged to the river (Hensel and Miller 1991; Hey et al., 1994). Similar surveys have been done in the same site as this study (Koreny et al., 1999), but groundwater dynamics in wetlands are still neglected by many wetland researchers.

This study focused on the interaction between groundwater and surface water in constructed wetlands, investigating variations in groundwater levels and quantifying the impact of flood pulses on exchanges between surface and groundwater. Our objective was to provide a primary understanding of flow patterns between surface water and groundwater within this region, and to identify meaningful parameters of the water balance model for the future.

Methods

Site Description

The Olentangy River Wetland Research Park (ORWRP) at The Ohio State University is located on a 30-acre site immediately north of the Columbus campus. Surface water flow through the constructed marshes is maintained by continuously pumping water from the adjacent Olentangy River. Water depths in the basins reach a maximum of approximately two feet, and the surface-water wetland stage varies with the pumping volume. Water discharges from the experimental wetlands through a V-notch weir and then flows back to the Olentangy River. The groundwater level at this site fluctuates according to seepage from the wetlands and flood events of the Olentangy River. The wetlands may discharge to groundwater during short periods of high flood stage of the Olentangy River, although generally they are a source of recharge for the river (Koreny et al., 1999).

The flat to gently rolling land surface at the ORWRP is underlain by approximately 100 feet of glacial and fluvial sand and gravel, with thin interbedded deposits of silty sand or silty clay. Silty clay, containing sand, gravel and cobbles, is prevalent from the surface to a depth of about 10 feet. This clay forms the surficial layer beneath which silty sand and gravel, and outwash deposited sand and gravel create a buried valley aquifer that dominates the ground water flow at the ORWRP site (Koreny et al, 1999). A total of 29 water table observation wells ('wells') and two recording piezometers (R1 and R2) were installed at the ORWRP site (Figure 1). Most wells were constructed using 2-inch PVC casing. Three wells were damaged or destroyed (B1, C2, and D3) and several were not properly backfilled, sealed, or protected.

Well D-1 and the two recording piezometers are protected above ground by 8-inch steel casings. Inside the casings, well depths range from approximately 13 feet to 3 feet below the ground surface. The total measured depth of R-1 is approximately 17 feet.

Field Methods

The field procedures in this study included measurements of the depth of groundwater in all accessible wells before the initiation of flood pulsing, and approximately 7 days later near the cessation of pulsing. An electric water level meter was used for all measurements. This meter consisted of a plastic tape graduated in hundredths of a foot, to which a stainless steel probe was attached that emits an audible signal upon contact with water. Measurements were made from a permanently marked point on each well casing. Groundwater measurements were conducted from February through May, 2004, during flood pulsing events. In addition, a shaft encoder water level sensor, permanently installed in R-1, continuously recorded groundwater levels from 15

January to 15 May, 2003.

Slug injection tests were employed in the field to measure the conductivity of groundwater in the bottomland hardwood forest area. During each slug injection, water was instantaneously added to the borehole, causing a rise in the original head above static level, after which the slug began to decay. This change in head was noted over time, plotted into a curve, and conductivity was calculated using the following equation (Domenico and Schwartz, 1998):

$$K=r^2 \ln(Lr^{-1})/(2LT0)$$

Where r = radius of the borehole, L = length of the intake area, and T0 is = intercept on the field curve where h/h0=0.37.

The elevation of the bottoms of the wetlands and the billabong were determined by measuring water depth at various sampling locations at specific staff stage levels. The coordinates of each sampling location were recorded by GPS, and the data were mapped using ArcGIS software.

Results and Discussion

Bottom Elevation Survey

An elevation map of the bottom of the billabong was created from measurements conducted on May 26, 2004 at 12:30 PM, (Figure 2). Of the 76 sampling locations, the greatest depth was 2.29 ft in the center of the billabong. The majority of the billabong area had a depth of less than 2 ft. The Kriging interpolation method was used to construct topography of the billabong elevation, which also demonstrated that the use of GIS can provide a visual interpretation of hydrology in wetlands research.

The bottom elevation of the experimental wetlands was investigated during Nov 2003. A three-dimensional perspective of these wetlands (Figure 3) and a contour map of the wetlands' elevation (Figure 4) were constructed. These maps were constructed based on the survey of multiple 20 x 18 sampling sites. All elevation values were calibrated using a benchmark elevation marker installed within the bottomland hardwood forest.

Topography within the ORWRP ranged from 723 to 729 ft above sea level. Using the 3D elevation model of the experimental wetlands, we generated plots to describe the relationships between water level, total area and total water volume (Figures 5A and 5B). Surfer 7.0 was used to process all elevation data and to construct these maps and algorithms. For a given staff gage water level, the corresponding total wetland area and volume of water can be estimated, based on the plots shown in Figure 5. In general, the two experimental wetlands are maintained with a water level of approximately 724.5 ft, in which case the area covered by water is about 180,000 ft^2, the total volume of water is about 120,000 ft^3, and the average water depth is approximately 0.7 ft.

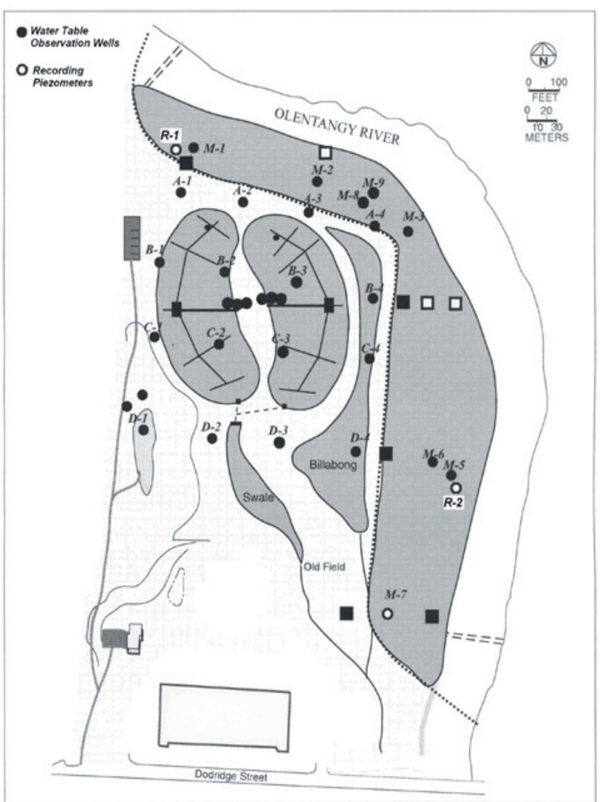

Figure 1. Groundwater table observation wells and recording piezometers.

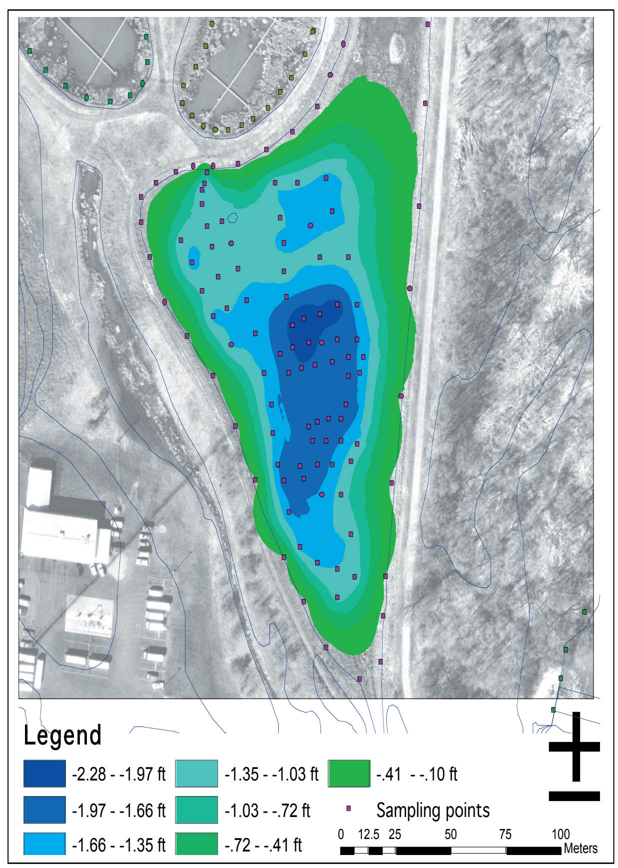

Figure 2. Bathymetric map of the Billabong.

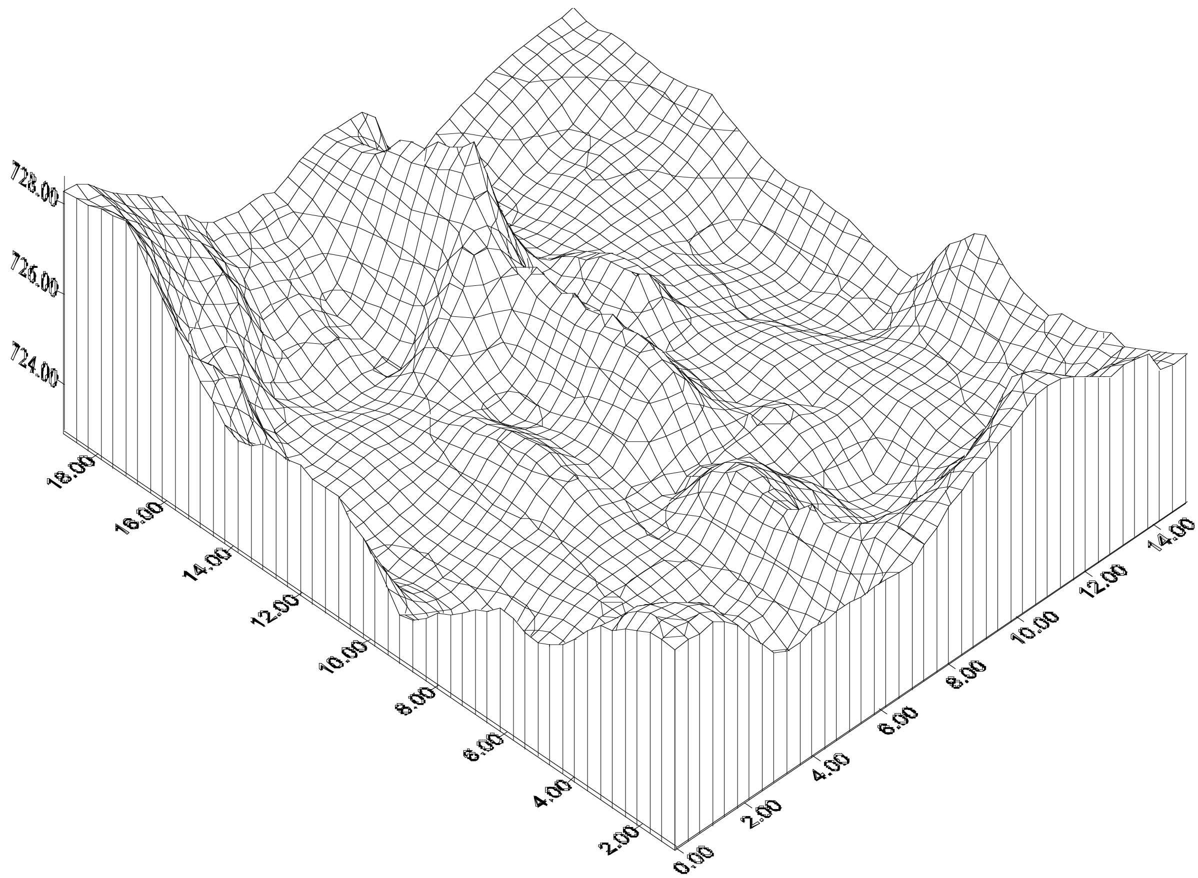

Figure 3. Three dimensional representation of Wetlands 1 and 2.

Based on these estimations, several additional hydrological parameters can be calculated, including residence time, water exchange rate, and total amount of dissolved solutes. These plots are essential in order to build a hydrological model to evaluate the water balance within this wetland system.

Changes in Groundwater Level Under Pulsed and Non-pulsed Hydrologic Conditions

The surface water levels of the ORWRP were automatically monitored by a Shaft Encoder Water Level Sensor and ground water levels of each observation well were measured manually just before and after the hydrologic pulsing period, and were plotted in a time series (Figure 6). Well C1 located at the boundary of Wetland 1, well A4 located between Wetland 2 and the Olentangy River, and well M7 located in the bottomland hardwood forest close to the Olentangy River were selected to illustrate impacts of the wetlands and river on local ground water fluctuations. During the period of this investigation, the ground water level of well C1 ranged from 724 ft to 725.5ft; ground water level of well A4 ranged form 723 ft to 725.5 ft; and ground water level of well M7 ranged from 721.5 to 724.5 ft (Figure 6). It is readily apparent that well C1 was mostly impacted by Wetland 1, as the groundwater level at the location of well C1 exhibited a very similar curve pattern as Wetland 1 from February 8 to May 12 (Figure 6). The other two wells, A4 and M7, were influenced by both the Olentangy River and the experimental wetlands, with a peak occurring around March 9 that corresponded to the peak of the two wetlands and a trough of the river, indicating a tradeoff between these two surface water systems. Furthermore, the crests of ground water levels of well C1 coincided with flood pulses delivered to the two wetlands at the beginning of each month, in contrast with the decreasing trend of well A4 and well M7 at the beginning of April.

A sequence of ground water levels in the wells occurred with distance from the wetlands to the river (Figure 6). Well C1 maintained the highest water level, and the lowest water level was consistently found in well M7. This was caused not only by the fact that the wetlands were always maintained at a higher water level than the Olentangy River, but also because the dam across the river was much closer to well M7 (Figure 1). This demonstrated that groundwater flowed from the wetlands to the river, and a sharp change in the river level caused by the dam produced a significant gradient in groundwater levels.

Conductivity Calculation

Slug tests were performed on wells M1, M5, and M7 to estimate the hydrological conductivity of this site (Figures 7 and 8).

A field survey on well M1 produced the following parameters: r=2.54 cm, L= 371.86 cm, T0 in test 1=25.34s, and T0 in test 2=26.91s. K, test 1 = 1.71×10^{-3} cm s^{-1} (1.48 m day^{-1}), K test 2= 1.61×10^{-3} cm s^{-1} (1.39 m day^{-1}).

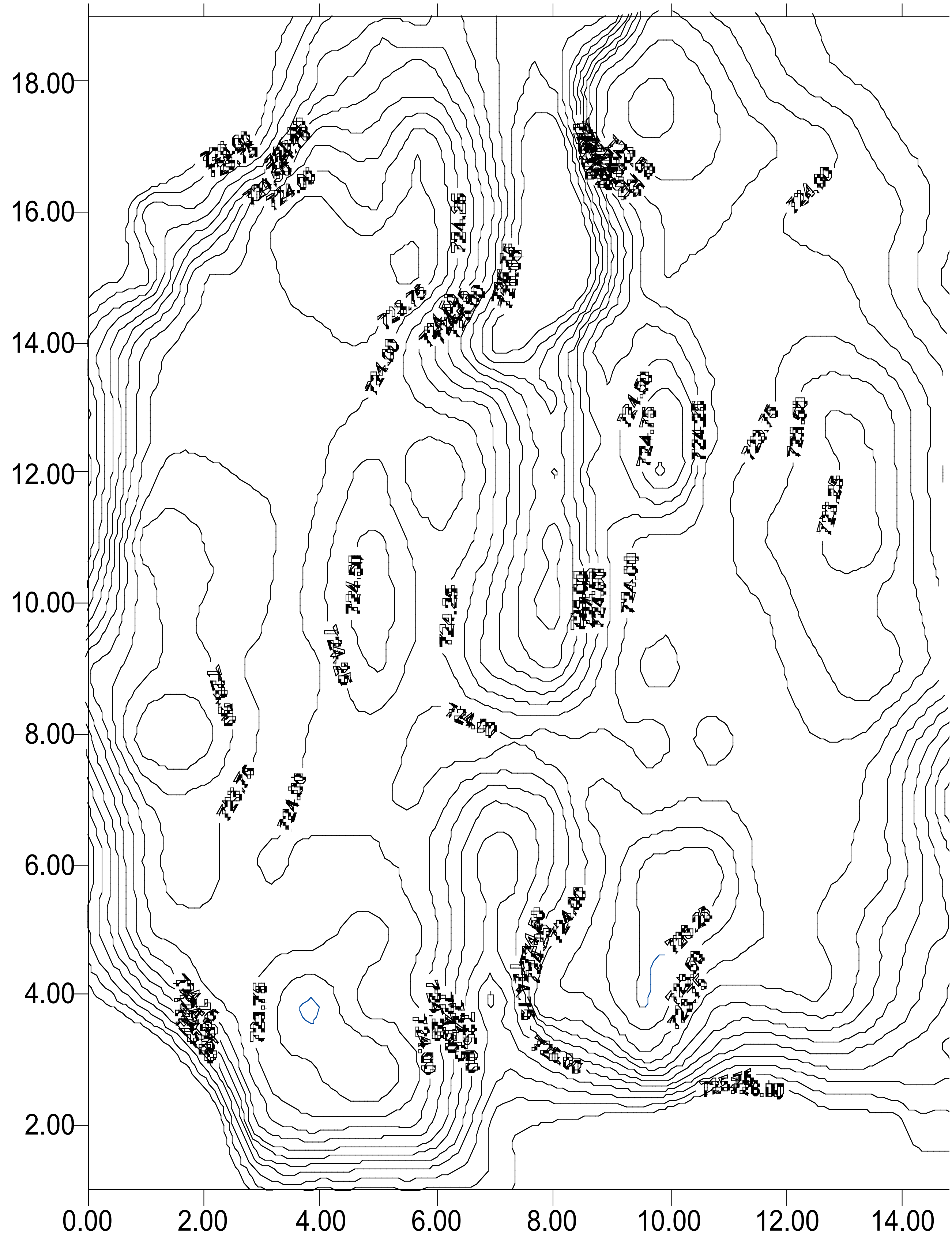

Figure 4. Contour map of Wetlands 1 and 2.

Parameters for well M5 are as follows: r=2.54 cm, L=282.85 cm, T0 in test 1=152 s, and T0 in test 2=207s. K was determined by Equation 2.1: K, test 1 = 0.35 x 10^{-3} cm s^{-1} (0.30 m day^{-1}); K, test 2 = 0.26 x 10^{-3} cm s^{-1} (0.22 m day^{-1}).

In the test on well M7, the water level dropped too quickly to be measured, indicating a larger conductivity value as compared with M1 and M5.

The hydrological conductivity values above are very similar to values calculated in a previous study, which ranged from 0.2 – 4.1 m day^{-1} (Koreny et al, 1999). There may be several reasons why the conductivity varies considerably in the bottomland hardwood forest, including differences in depth of the wells and in geology. As a general rule, sandy soil is found close to the river because sand particles settle out more quickly as the river floods. From the field elevation survey, well M5 located on the lower site flooded much more frequently compared with the sites surrounding wells M1 and M7. Frequent flooding from the river would deposit a lot of sediments around well M5 and could form clay and silt layers with a much lower conductivity than sandy soil. Extended periods of anaerobic conditions allow for the accumulation of organic matter, which could fill pore spaces in sandy soil, decreasing conductivity.

Groundwater Flow Analysis

The common situation of hydrogeology in this site is that water seeps from the wetland gravels through the groundwater flow system and discharges back to the Olentangy River, because the higher water level of the wetlands causes an upward vertical gradient close to the Olentangy River (Koreny et al, 1999). However, since river level varies frequently with precipitation, sometimes the river level may be higher than the adjacent ground level and may recharge the groundwater system.

Groundwater velocity can be estimated by Darcy's law and the groundwater contour map. The result of the velocity (Darcy's velocity) of groundwater flow from the river to the bottomland on the sites of well M1 and M5 on Nov 1, 2003, was calculated as below:

$$q=-K\Delta h/\Delta l \quad \text{(Darcy's law)}$$

where K = conductivity, using the average value of the two slug tests on the wells, and $\Delta h/\Delta l$ = the water head gradient. For well M1, K = (Ktest1+ Ktest2)/2 = 1.43 m/day; for well M5, K = (Ktest1+ Ktest2)/2 = 0.27 m/day. ($\Delta h/\Delta l$) was estimated by: (the groundwater level in the well – river level) / the distance between the river and well. For well M1, ($\Delta h/\Delta l$) = -0.0065; for well M5, $\Delta h/\Delta l$) = -0.0118. Groundwater velocities on the wells were calculated as below:

For well M1, q = 0.93_10-2 m/day;

For well M5, q = 0.32_10-2 m/day.

From the calculations above, groundwater flowed very slowly and could be considered to be at an equilibrium state at that time. This meant that flluctuations in the river level influenced groundwater patterns in the bottomland over a very short time period, with the interaction being almost

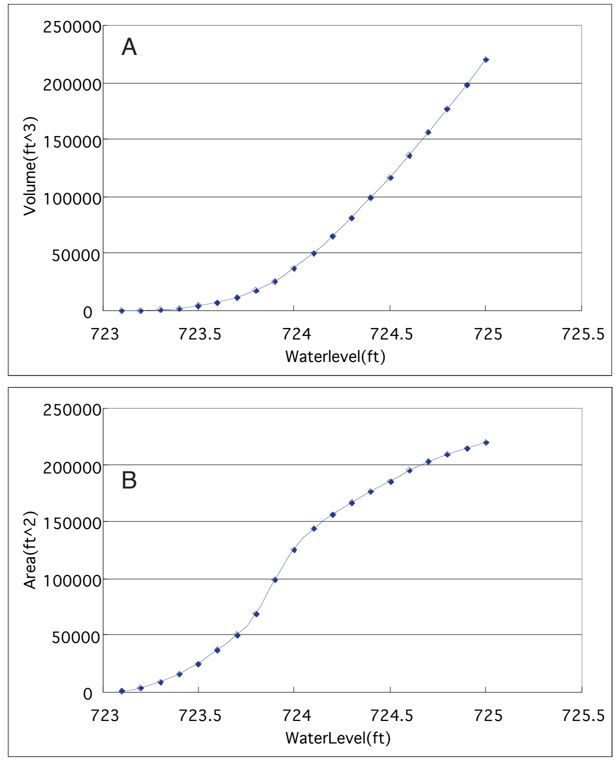

Figure 5. Relationship between water level and A) total volume of water; B) surface area covered by water, in Wetlands 1 and 2.

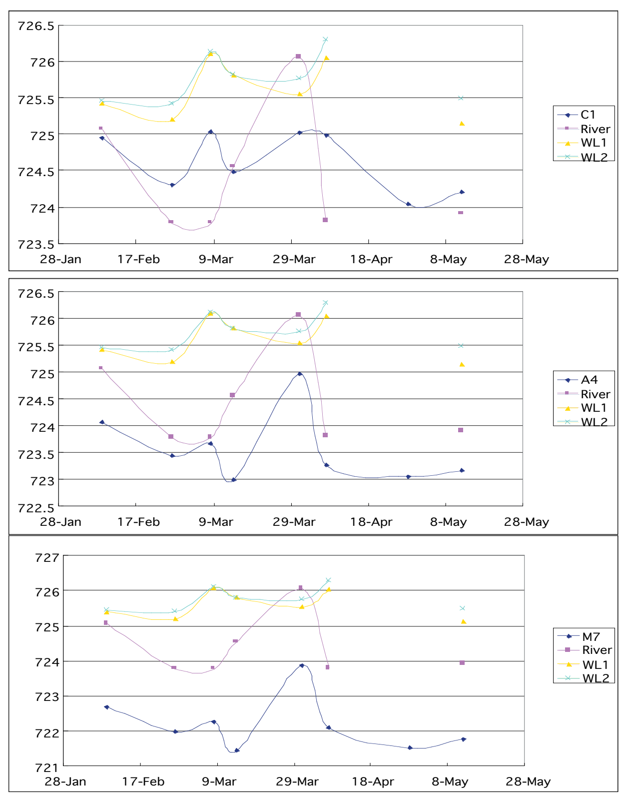

Figure 6. Groundwater levels recorded before and after hydrologic pulses in A) well C1, B) well A4, and C) well M7, in relation to surface water levels in the Olentangy River and in Wetlands 1 and 2.

simultaneous.

Conclusions

The bottoms of the created wetlands are influenced mostly by the adjacent river in hydrological aspects, while groundwater level around the wetlands is mainly controlled by the wetlands. A significant gap existed in groundwater levels, caused by the dam across the River. The pulsing events of the wetlands significantly raised the groundwater level in well C1, but did not change the groundwater level of well A4 and well M7 in the same manner.

The changes between the groundwater in the bottomland and the adjacent river are very frequent and sometimes would reach an equilibrium state; groundwater levels were very easily changed by fluctuations in the river.

The flood pulsing to the bottomland from the river may change the soil and geological profile in the bottomlands, affecting physical characteristics such as hydrological conductivity.

Acknowledgments

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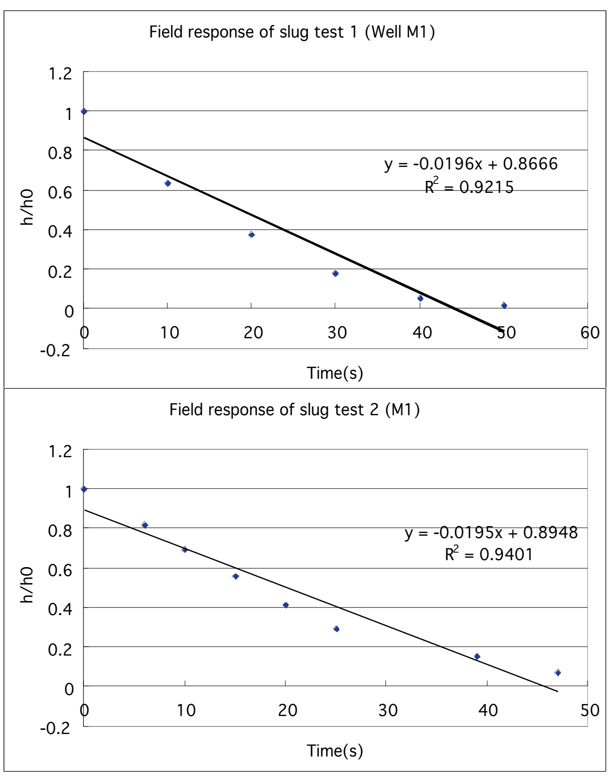

Figure 7. Slug test to measure hydrologic conductivity of groundwater in well M1.

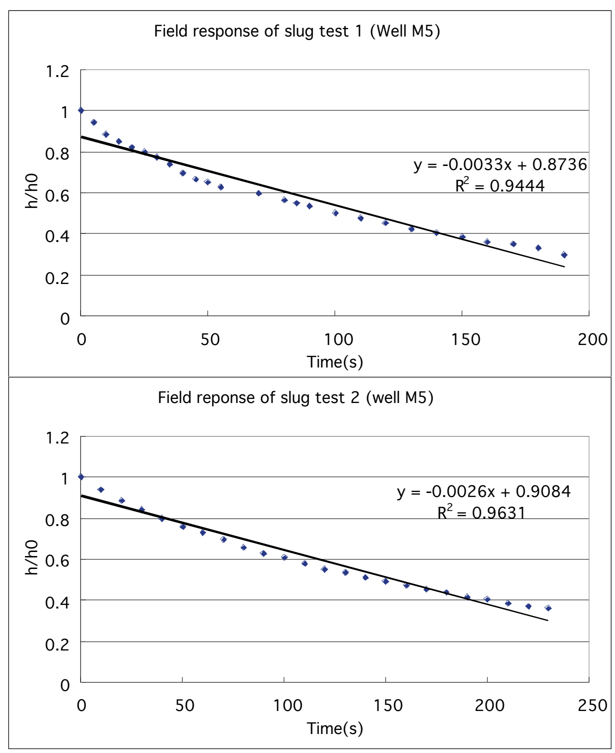

Figure 8. Slug test to measure hydrologic conductivity of groundwater in well M5.